Total Evaporation Estimation of Sugarcane Using the Scintillation Technique

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Abstract

South Africa is a water scare country and consequently, there is pressure on authorities as well as water users, to manage and utilize our water in a sustainable manner. Much research has been focussed on water use by different vegetation, in particular forestry. The result of some of this research is that commercial forestry has now been declared a Stream Flow Reduction Activity. Water managers have recognised that there is still a need for further research on other land uses and their potential water use, in particular sugarcane. However, because of the complex nature of runoff generation, it is extremely difficult to provide accurate estimates of the potential for sugarcane and other crops to reduce runoff. An estimate of the total evaporation from these land uses will provide scientists and managers alike with a more direct estimate of water use.

Recently, a technique, known as scintillation, which is able to assist in estimating total evaporation from both homogeneous and heterogeneous land surfaces has been applied by the CSIR and UKZN in South Africa. This technique provides area averaged surface fluxes at spatial scales of up to 5 km and may prove useful in both water and energy balance research, and thus be used to examine the influence of vegetation type within a catchment.

In this paper, we describe the application of the scintillation technique to a dryland sugarcane site in the KwaZulu-Natal Midlands, present results from this application and provide some recommendations for the application of this method in water resources planning in South Africa.

1. Introduction

Since the implementation of a new National Water Act (1998) in South Africa, there has been increased pressure placed on all potential water users. The largest water user from a land use perspective is commercial timber production which has been declared a Stream Flow Reduction Activity (SFRA). Consideration of the water use of other land based activities has been intensified as other potential SFRAs, of which sugarcane is one, have been identified. Catchment response data necessary for these considerations are rarely available and thus, much of the assessment of water use by these crops has been focussed on estimates of total evaporation (Et), typically using an energy balance approach.

Methods to estimate Et have advanced considerably in the past decade. Amongst these advances has been the emergence of scintillation as a method to measure average sensible heat flux, a vital component of the energy balance, over an area. The technique provides area averaged sensible heat fluxes measured by an instrument called a scintillometer at spatial scales up to 10 km. A strength is that the area to which the technique can be applied may differ in size as well as incorporate different vegetation types. The sensible heat flux component needs to be measured in conjunction with the other energy balance components i.e. net radiation and soil heat flux.

In this paper, we describe a study in which the evaporative water use of sugarcane has been estimated using the scintillation technique and where, in addition to sensible heat flux being measured with a scintillometer, the other components of the energy balance as well as soil moisture have been measured for one year. The application of this technique may prove to be very useful for future hydrological studies and aid in decision-making, as knowledge and data obtained could provide a basis for decisions related to the implementation of SFRA’s in South Africa.

2. Site and Equipment Description

2.1 The Scintillation Technique

A scintillometer is an instrument consisting of a transmitter and a receiver (Figure 2.1). It functions over a horizontal path by emitting a beam of light (electromagnetic radiation) from the transmitter to the receiver, which is able to detect scintillations.

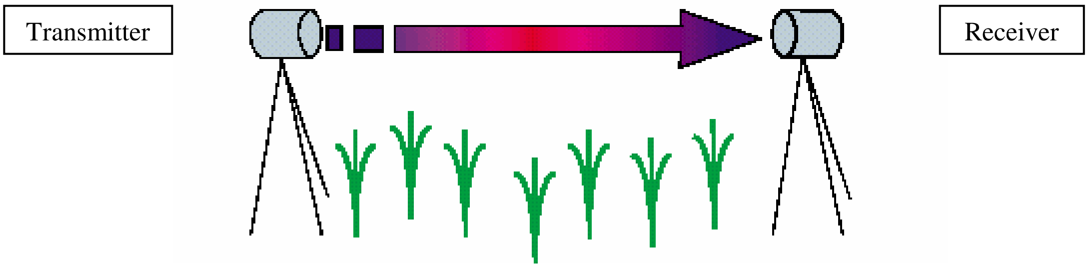

Figure 2.1: Simple Illustration of the Scintillation technique (Kite and Droogers, 2000)

This scintillation method is used to provide area averaged surface fluxes at spatial scales up to 10 km. Electromagnetic radiation passes through the atmosphere and is distorted by a number of processes such as scattering and absorption by constituent gases and atmospheric particles of the atmosphere, which remove energy from the beam and thus lead to attenuation (Wageningen University and Research Centre 2003 and Meijninger, 2003). The most important mechanism, which influences the propagation of EM radiation, are small changes in the refractive index of air (n). These changes lead to intensity fluctuations known as scintillations (Meijninger, 2003). An example that clearly shows the distortion of wave propagation by the turbulent atmosphere is the twinkling of stars. Atmospheric turbulence is described as three-dimensional air motions or eddies, which have sizes ranging between millimetres to tens of metres (Wageningen University and Research Centre, 2003). Atmospheric turbulence is the most effective transport mechanism for many scalar quantities, such as sensible heat (H) and water vapour (L_vE). These eddies transport both heat and water vapour with their refractive indexes differing from the surrounding area, hence resulting in refractive index fluctuations or scintillations (Wageningen University and Research Centre, 2003; Meijninger, 2003).

2.2 Site Description

The research catchment is located near Greytown in the Natal Midlands adjacent to the Council for Scientific and Industrial Research (CSIR) Two Streams experimental catchment which, for a number of years, has had both water and energy balance research taking place. The research site has the advantage of being monitored by an Automatic Weather Station (AWS) run by the CSIR. A number of other measurements being made by the CSIR at the site will be useful for comparison.

A large aperture scintillometer has been set up over a sugarcane catchment with a transect length of 1.62 km. The transmitter is located on a lookout tower (Figure 2.2). The reason for the selection of this is that there is 220V AC power supply. A regulator converts this into 12V DC at which the scintillometer operates. The transmitter has a high power demand and therefore needs to be located near a high power source.

The receiver uses far less power and is able to run for approximately 7-10 days on two 96AH batteries. Batteries are therefore changed weekly and the instrument re-launched and re-aligned. Data collection takes place at the receiver and is logged at one minute intervals. The receiver is bolted onto a strong box, in which the signal processing unit (SPU) is located as are the batteries. The data is transferred onto a laptop (Figure 2.2).

Figure 2.2 The Scintillometer Transmitter (right) and Receiver (left) located at the Two Streams sugar experiment

3. Field Measurements, Calculations and Assumptions

3.1 Primary Climatic Data Collection
Primary data has been collected at an Automatic Weather Station located at the research site. This AWS is maintained by the CSIR and has provided reliable data for approximately 8 years and includes the measurement of the following:

- Total incoming solar radiation
- Air temperature
- Humidity
- Wind speed and direction
- Rainfall

This data has proved to be useful especially in assessing anomalies in any of the energy balance components.

3.2 Soil Moisture Measurement
Soil moisture has been monitored for the duration of the project gravimetrically at the early stages of the project, and using Time Domain Reflectometry (TDR) measurements since April 2005. Soil moisture measurement using the TDR has been measured at 4 sites across the transect at depths of 30, 60, 90 and 120cm. The soil moisture data is used in the calculation of the soil heat flux – a component of the energy balance.

3.3 A-Pan data
A-Pan data has been collected at a nearby site by the South African Sugar Research Institute (SASRI). This data contains large gaps, but offer some indication of evaporation.

3.4 The Energy Balance
Turbulent exchange of energy and mass takes place between the earth's surface and the atmosphere with the sun providing energy in the form of net radiation (R_n). Net radiation is that portion of incoming solar radiation which is not reflected at the earths surface. This energy is best described or broken below: (Meijninger, 2003).

$$R_n = H + L_vE + G_s$$

Where:
R_n = Net Radiation
H = Sensible Heat Flux Density
L_vE = Latent Heat Flux Density
G_s = Soil Heat Flux Density

The summation of these three components gives the total net radiation. Sensible Heat Flux Density (H) can be defined as the warming of the air by the underlying surface. Latent Heat Flux Density (L_vE) is the proportion of net radiation that will be used to evaporate any water that may be present at the surface. Soil Heat Flux Density (G_s) refers to the proportion of net radiation which is transferred into the soil (Meijninger, 2003).

Total incoming solar radiation is measured by the CSIR at the AWS, situated near the transmitter tower. Albedo has been provisionally estimated so that net radiation can be estimated. Outgoing radiation has not been measured due to a lack of availability of suitable instruments. For the purposes of this paper we have assumed an albedo of 20%. Therefore, the net radiation presented comprises 80% of the total incoming radiation. Plans have been established to determine the albedo both within and above the sugarcane canopy for various stages of growth and angles of incident solar rays. The albedo was kept constant at 20% so that seasonal fluctuations in the energy balance components could be noted. Once albedo has been estimated at different stages, this will be incorporated into the energy balance.

Sensible heat flux has been measured by the scintillometer. This has been logged every minute and provided reliable data since 27 September 2004 with the exception of the following:

- Misty conditions which results in transmission failure.
- Periods when the instrument was removed due to security reasons or repair.
- Condensation on the receiving lens. This occurs at night time. This is resulting in refraction of the transmitted light and giving errors. This has been corrected by ignoring evening sensible heat fluxes.

Soil heat flux has been estimated using the following equation: (Blight, 2002)

$$G_S = z_g(\Delta T)C_G P_G$$

Where:

- z_g = depth of soil heated (m)
- ΔT = the average measured rise in temperature over depth z_g
- C_G = the specific heat of the soil (kJ/kg/^{o}C)
- P_G = bulk density of the soil (kg/m^3)

The soil thermometers have been placed in soil under an ‘average’ canopy. This represents a vegetative average in terms of both yield and age. The thermometers have been moved once to maintain these average conditions.

Therefore the following field measurements have been measured at the site:

- Average soil temperature change has been measured using soil thermometers buried at depths of 50 and 250mm respectively. Temperatures have been recorded at 30 minute intervals continuously since November 2004 with the exception of a few period of logger failure.
- Soil density has been measured by sand replacement and was found to be approximately $1390 kg.m^{-3}$.

Latent heat flux (evaporative term) can therefore be deduced by making it the subject of the energy balance equation. Therefore: $L_vE = R_n - H - G_s$

3.5 Rainfall

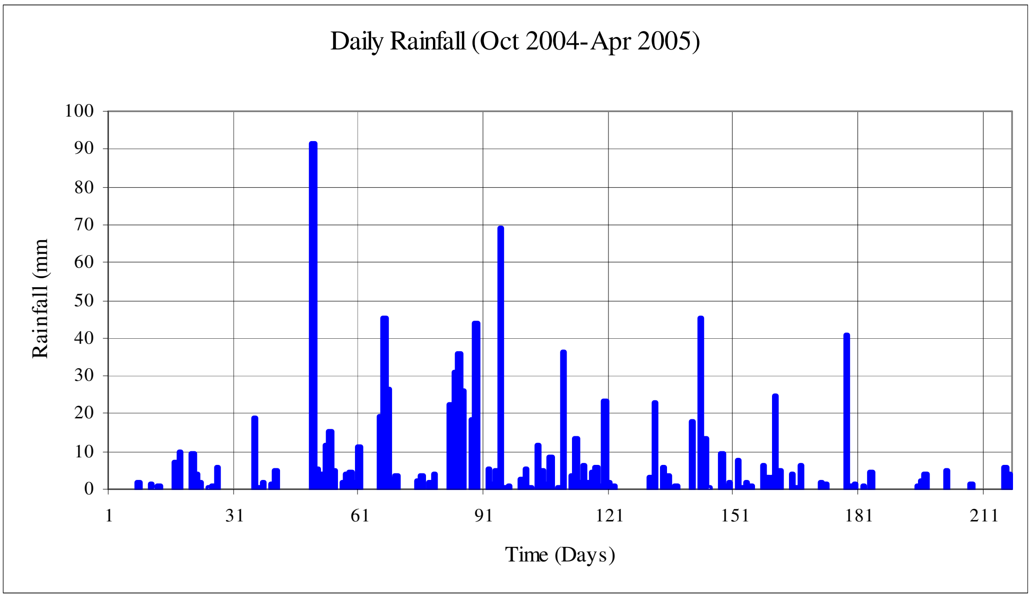

Figure 3.1 Daily rainfall for the period October 2004 – April 2005

Figure 3.1 shows the rainfall distribution from October 2004 until the start of May 2005. It can be seen that it has been a good agricultural season with rain falling consistently and following the normal seasonal trend. Good rains have fallen well into the dry season. Personal communication with the local farmer confirms this. Accurate rainfall data is essential in this research as it provides a limit to the evaporative process.

4. Presentation of Results

Components of the energy balance for selected days in November, December, January, March and May for the season 2004-2005, are shown below. Figures 4.1 – 4.10 show the relative contribution of the different energy balance components for different times of the year. The area under the latent heat curve has been integrated to give a quantitative estimate of total evaporation for each day. The associated primary data for the periods have also been plotted. This has assisted in interpreting the energy balance.

4.1 November 2004

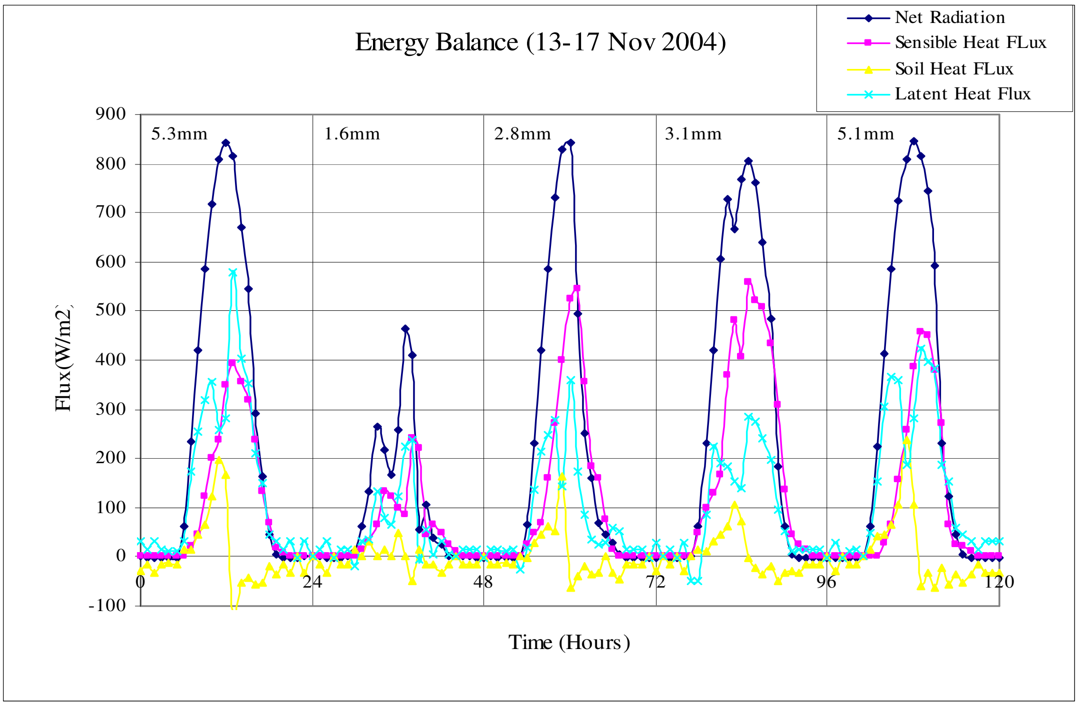

Figure 4.1 Energy Balance for 13-17 November 2004. Figures at the top represent daily Et estimates in mm.day^{-1}

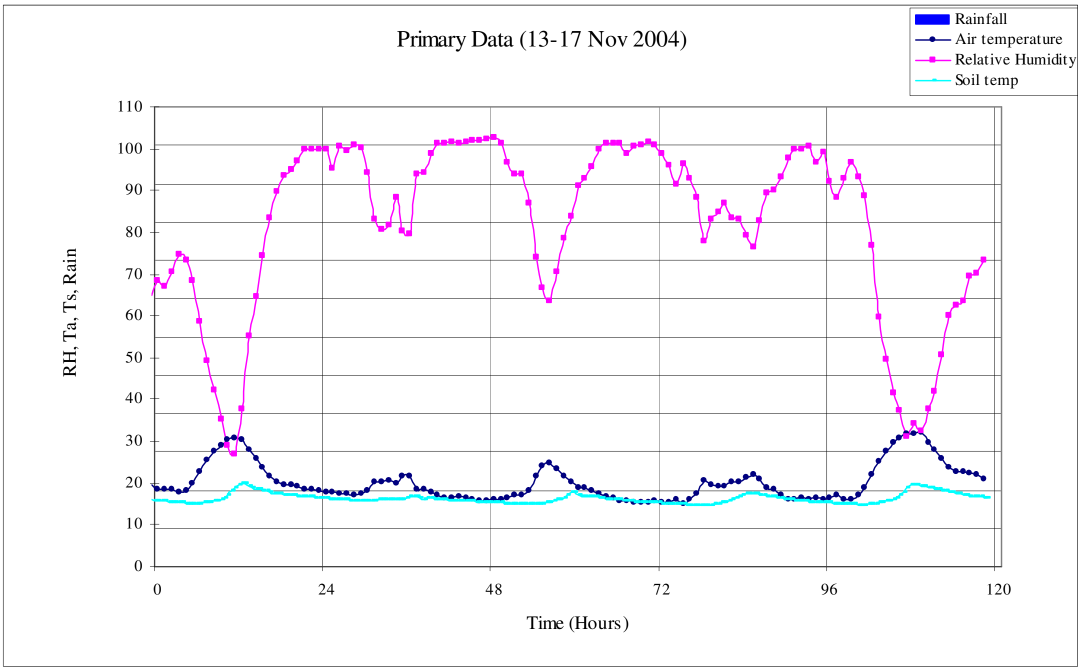

Figure 4.2 Primary Data Plots for 13-17 November 2004

Analysis of Figures 4.1 and 4.2 showed that total evaporation, as expected, is closely correlated with net radiation, air temperature and relative humidity. For the period 13-17 November the highest total evaporation estimates are 5.3 and 5.1 mm per day (13 and 17 November respectively). These days also record the highest air temperatures (32^{o}C) and lowest relative humidity (30%). The soil was also relatively dry at this stage with only 73mm falling since the start of October 2004 until 17 November. Soil moisture limits total evaporation for this period. Soil heat flux on these days was significant reaching values of 200W.m^{-2}. This can be attributed to the lack of moisture reducing the evaporative cooling effect. The result is a large range of average soil temperature. The rapid decline in soil heat flux after the peak in the early afternoon occurs when the soil begins to radiate more heat than it receives from solar radiation and hence a negative flux is recorded. The total evaporation average for the period 13-17 November 2004 is 3.6mm.day^{-1}

4.2 December 2004

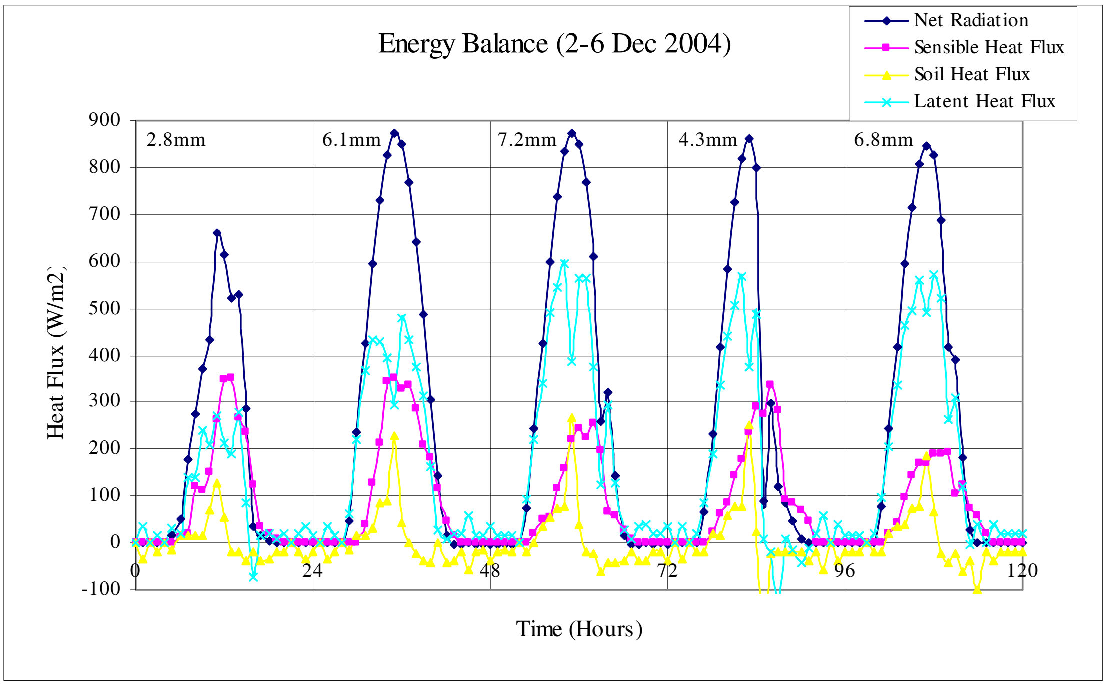

Figure 4.3 Energy Balance for 2-6 December 2004. Figures at the top represent daily Et estimates in $mm.day^{-1}$

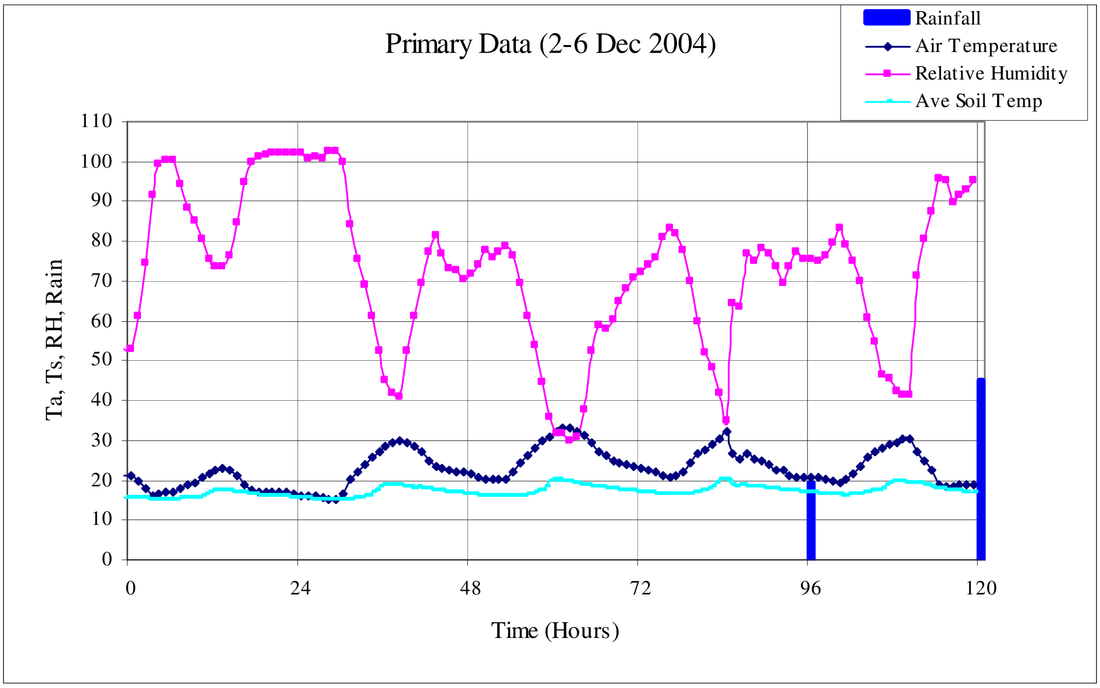

Figure 4.4 Primary Data Plots for 2-6 December 2004

During the period 2-6 December 2004, two significant rainfall events occurred. Although only daily rainfall is provided, relative humidity and air temperature indicate that the rain fell at a high intensity with intense convective rainfall being a common occurrence at this time of the year. Total evaporation reached a maximum (7.2mm) for this period on 4 December. The net incoming radiation for 3-6 December 2004 is very similar to that of 13 and 17 November 2004, with similar relative humidity. The sensible heat fluxes are lower in December than in November. Latent heat flux on the other hand is higher in December than in November. This increase in total evaporation is thus assumed to be a result of increased moisture availability. This is confirmed by Figure 3.1with good rain occurring in late November. Soil heat flux is also very high over this period comprising approximately 20% ($260W.m^{-2}$) of total incoming radiation. The total evaporation average for the period 2-6 December 2004 is $5.4mm.day^{-1}$

4.3 January 2005

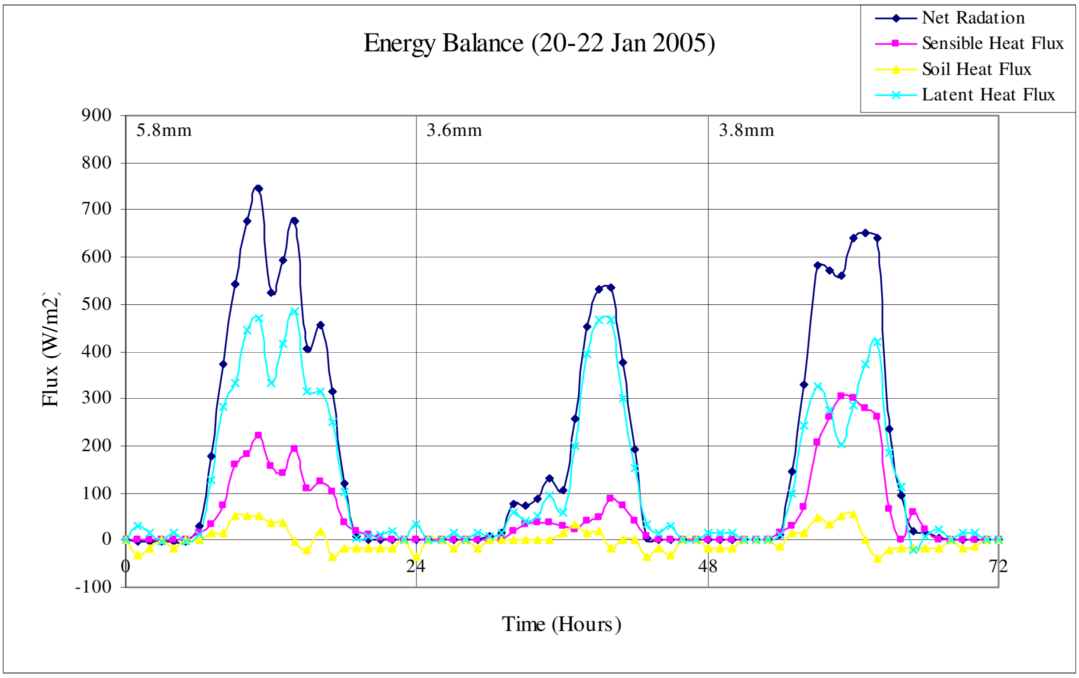

Figure 4.5 Energy Balance for 20-22 January 2005. Figures at the top represent daily Et estimates in mm.day^{-1}

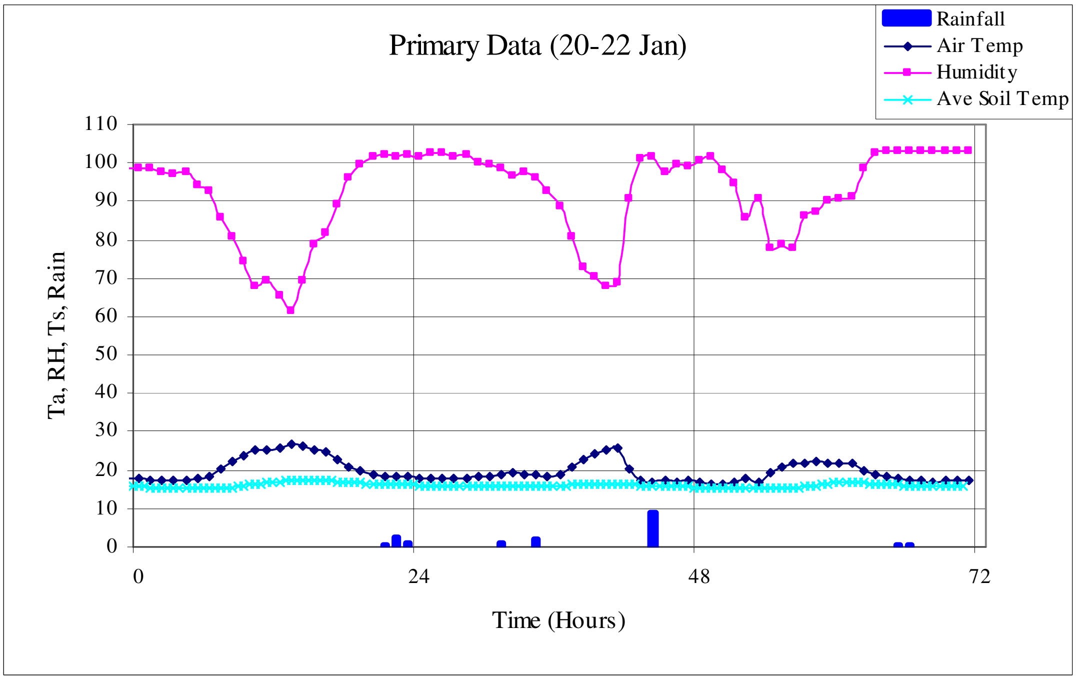

Figure 4.6 Primary Data Plots for 20-22 January 2005

Due to security reasons the Scintillometer was removed over the festive season and returned at mid January. This resulted in a shortage of sensible heat flux data for early January. Figure 4.5 shows total evaporation for late January (20-22 January 2005). It is assumed however, to underestimate total evaporation in January. Average air temperature for January should be higher than temperatures represented above. The analysed days are therefore thought to be cooler than the average in January, reaching a maximum air temperature of only 27°C over this period. This is more than likely due to the insulation of clouds with net radiation reaching only 740 W.m^{-2} and fluctuating throughout the day depending on the clouds (20 January). On January 21, the net radiation is well below the daily average. Good rains occurred in January and therefore the major limit to total evaporation for the graphed period is thought to be incoming radiation. However, there is a reasonable sensible heat contribution showing that radiation is not entirely limiting. Soil heat flux is much lower than it was for November and December indicating the cooling effect of evaporation from the soil and crop. The low range in diurnal air temperatures could

possibly also contribute to the low range in diurnal average soil temperatures. The total evaporation average for the period 20-22 January 2005 is 4.4mm.day^{-1}

4.4 March 2005

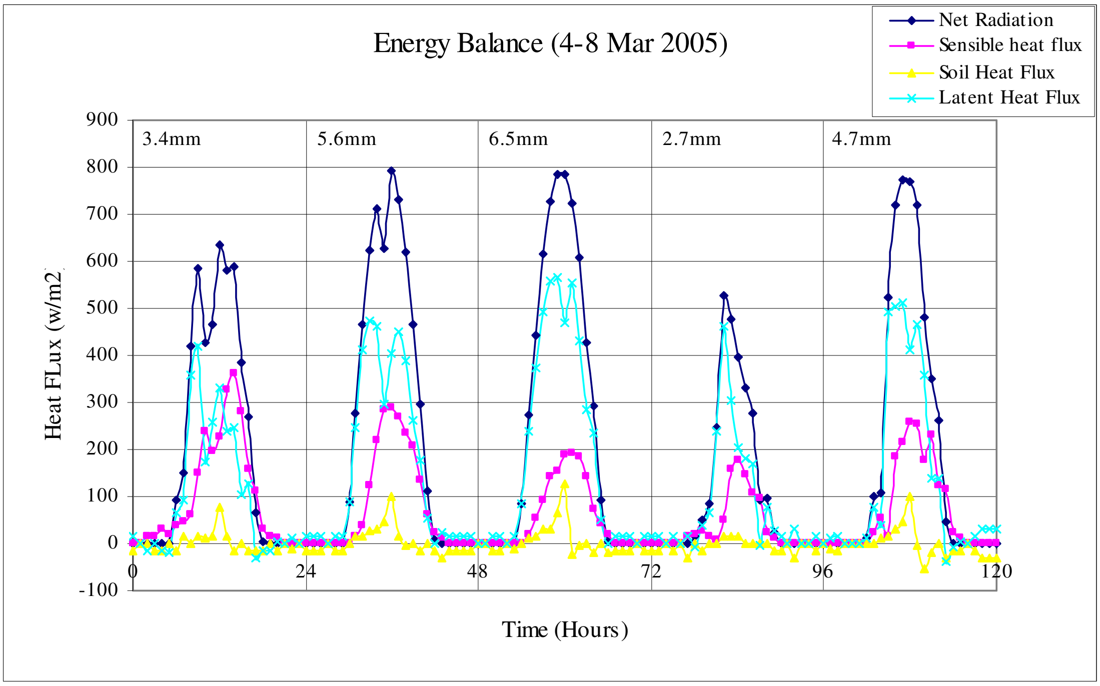

Figure 4.7 Energy Balance for 4-8 March 2005. Figures at the top represent daily Et estimates in mm.day^{-1}

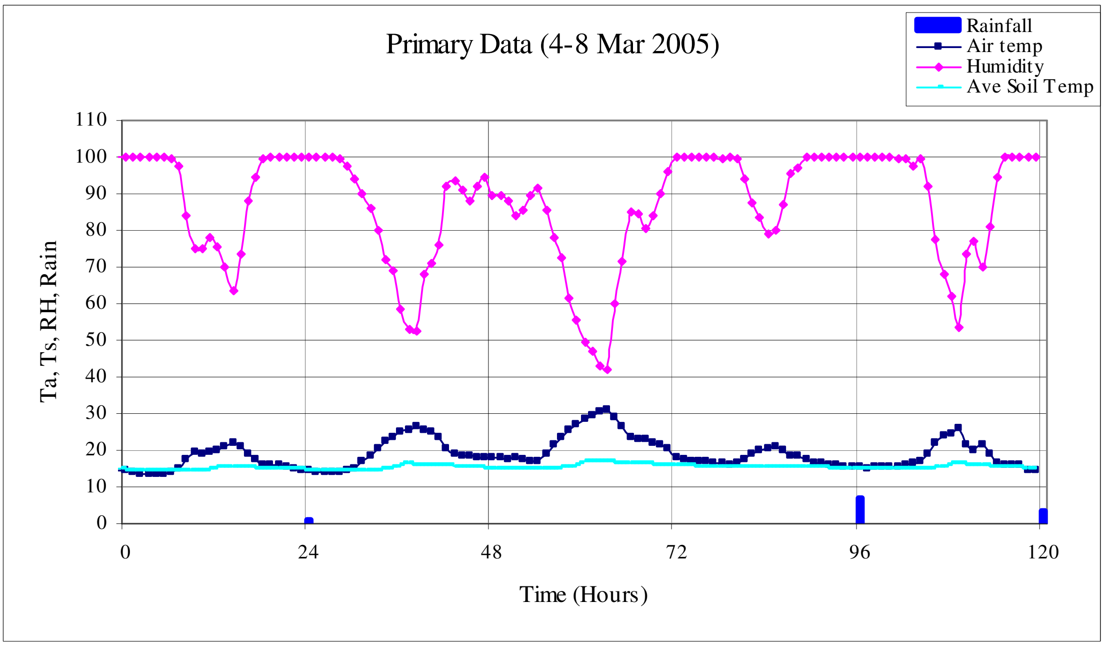

Figure 4.8 Primary Data Plots for 4-8 March 2005

Total evaporation estimates for March 4-8 are very similar to those obtained in January. There are, however a number of differences in net radiation and soil heat flux. Net radiation was higher for this period in March due to less cloud cover. This resulted in higher maximum air temperatures and the cooler season resulted in lower minimum air temperatures. This contributed to a higher soil heat flux proportion than experienced in January. Moisture is thus less of a limiting factor to the evaporation process than incoming radiation for March 2005. It is assumed that as conditions dry out, the sensible component comprises a correspondingly larger percentage than the latent component. Conditions had not dried out enough by this time for this to be concluded. The total evaporation average for the period 4-8 March 2005 is 4.6mm.day^{-1}

4.5 May 2005

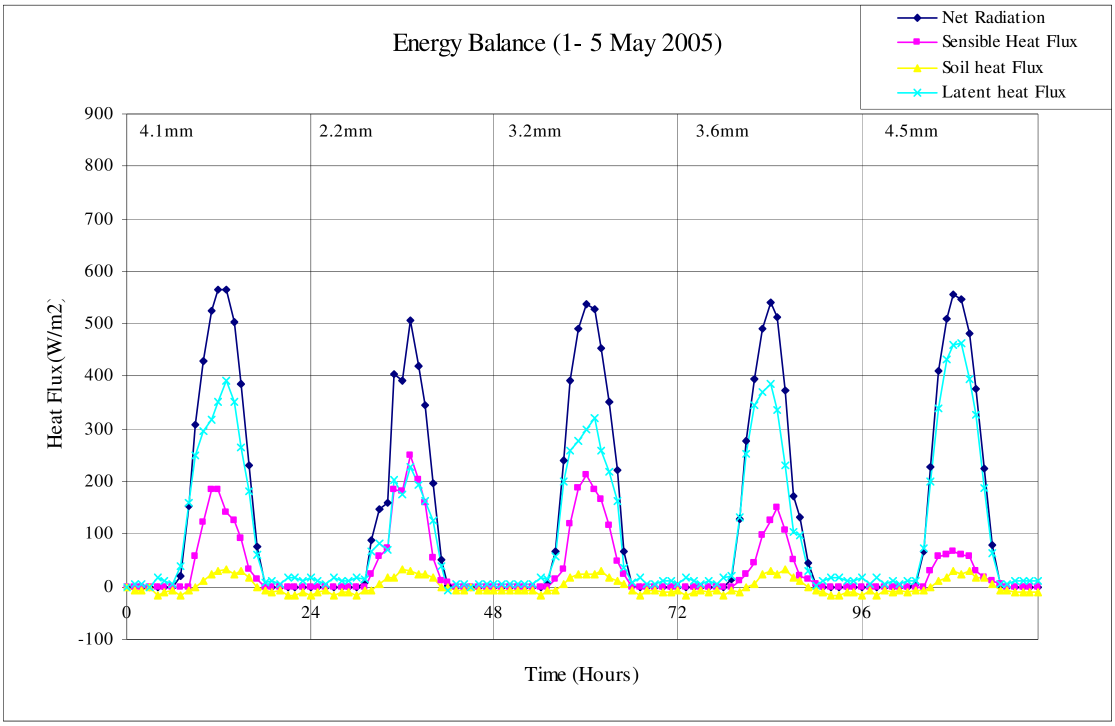

Figure 4.9 Energy Balance for 1-5 May 2005. Figures at the top represent daily Et estimates in mm.day^{-1}

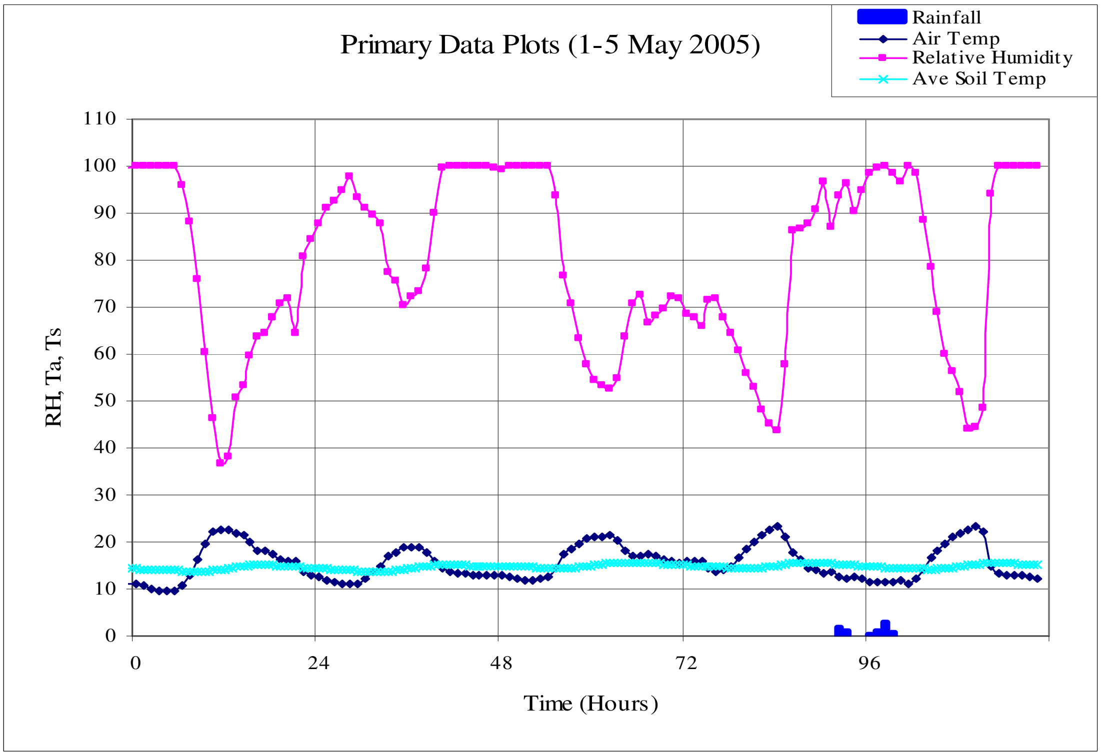

Figure 4.10 Primary Data Plots for 1-5 May 2005

Net radiation is low at approximately 520 W.m^{-2} for this period as the sun is approaching the Southern hemisphere winter solstice. There is thus a low amount of energy available for distribution amongst the energy balance components. A relatively low soil heat flux (with a maximum of approximately 45 W.m^{-2}) is recorded. Total evaporation is the lowest for the analysed period from November 2004 – May 2005. Soils are still relatively moist (Figure 3.1) and the demand from the atmosphere is low with low net radiation. This combination results in the latent flux still providing a large portion of the energy balance even though total evaporation estimates are low. The total evaporation average for the period 1-5 May 2005 is 3.5mm.day^{-1}

4.6 Summary of Results

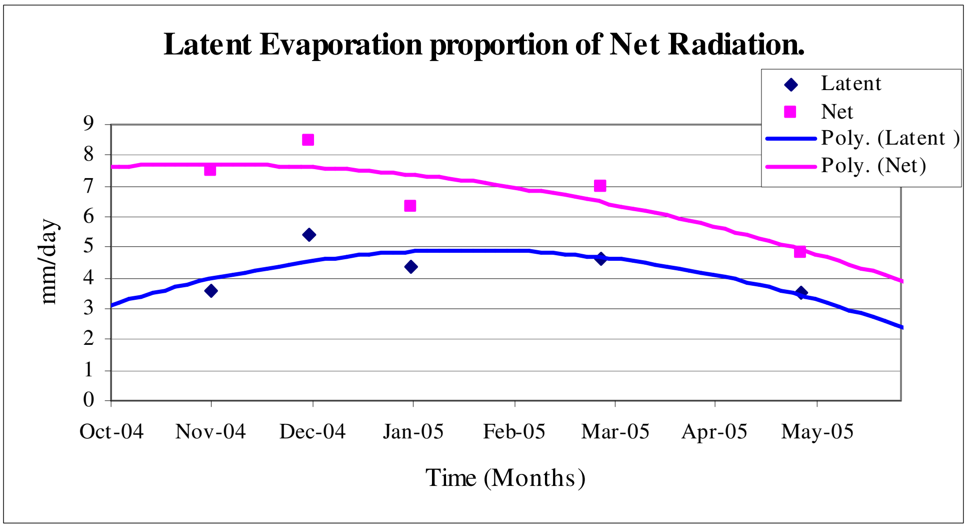

Figure 4.11 Monthly averages of latent evaporation and net radiation for the period October 2004 – May 2005.

A polynomial trend line has been fitted to total evaporation averages, as well as quantitative averages of net radiation ($mm.day^{-1}$) calculated for selected days in selected months from November 2004 to May 2005. The trend is as expected with substantially more evaporation occurring in the summer where soil moisture limits the evaporation process less than radiation. Net radiation is also at a peak for these months. It is assumed that the crop is able to come close to the atmospheric demand and results in relatively high evaporative losses for the summer period. The availability of moisture cannot merely be compared from one month to the next but needs to be considered in conjunction with the atmospheric demand (net radiation). From figure 4.11, the availability of moisture seems to be more of a limiting factor in the late winter/early summer months (October 2004) than it is during the summer and early winter months. The reason for this is the accumulation of water in the soil profile over the rainy season. As winter approaches, this supply is gradually decreased. Good rains have fallen over the rainy season (Figure 3.1) which has resulted in the total evaporation comprising 70% of net radiation in May 2005. This has been possible due to the decreased atmospheric demand for this time of the year (May). Figure 4.11 is based upon a small period of 3-5 days within each month. Further analysis should confirm the trends evident in the above graph. It is worth noting that the value obtained for January 2005 is an underestimate due to the fact that the days analysed were not climatically representative.

4.7 Scintillation trends

Figure 4.12 shows the general seasonal trend of sensible heat for the period from October 2004 until May 2005. As expected, the general trend shows a decline in sensible heat during the summer months as portrayed by the fitted polynomial trend line. The assumption in Figure 4.12 is that the condensational effect on the receiving lens is relatively constant over the season as the plot includes both day time and night time sensible heat fluxes.

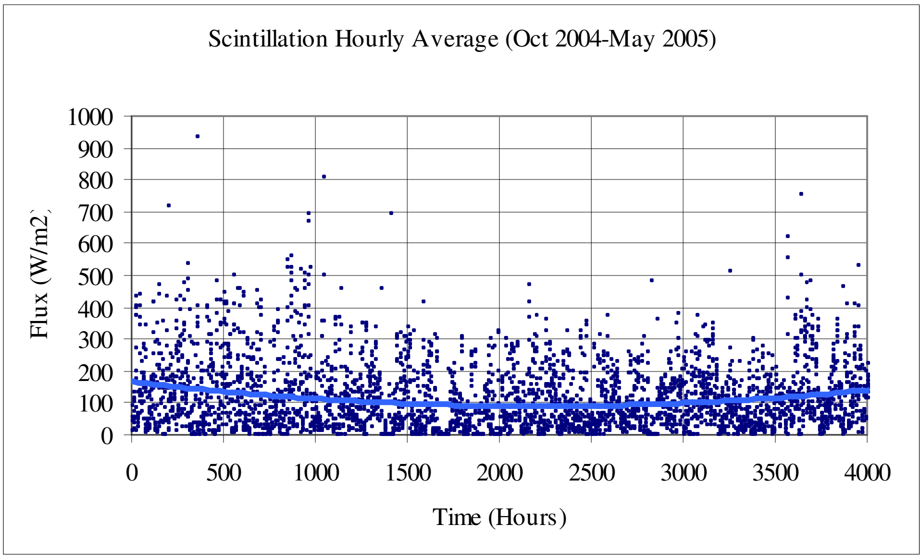

Figure 4.12 Sensible heat flux hourly averages for the period October 2004 - May 2005

5. Conclusions

Improved understanding of the water use by sugarcane and its variability throughout the season is being obtained through this study. As expected, net radiation provides driving force to total evaporation and fluctuates depending on the time of year. The availability of soil moisture has proved to be the limiting factor to the evaporative process for a portion of the year. This means that the crop is unable to meet the atmospheric demand in terms of moisture. In the wetter summer months and early winter months however, when soil moisture is readily available, the limit to evaporation is radiant energy or the crop possibly reaching its transpiration rate limit. The potential water use by sugarcane is therefore reached in the wetter summer months. Once albedo measurements have been incorporated, and analysis for the remaining months done, total evaporative estimates will be more accurate and the seasonal changes more evident. Estimates of total evaporation and their seasonal variability can prove to be useful for comparative studies to determine whether sugarcane should be declared a SFRA.

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